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FUEL CONSERVATION CAPABILITY AND EFFORT
BY COMMERCIAL AIR CARRIERS

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INTRODUCTION

Fuel conservation in recent months has become the watchword of the entire population. More specifically, the commercial air transportation industry is directing increasing attention to this subject because its well being is tied to efficient fuel usage. The embargo on imports of Mid-East oil to this country in late 1973 prompted many air carriers to review procedures and change operating style in an attempt to save fuel. The years 1970 and 1971 proved to be economically adverse for United Air Lines and the fuel bill came under close scrutiny. Procedures and techniques affecting fuel usage were revised at that time, and those changes appear to still be valid in view of the present fuel situation. The procedures and capabilities discussed herein, while they may be representative of those of any major air carrier, are those used by United Air Lines.

PRE-FLIGHT PLANNING

COMPUTER CAPABILITY

UAL automatic flight planning is done in a Sperry Rand Univac 1108 computer. Flight plans are computed for all flight segments 350 nautical miles or more in length.

Actual weights, rather than standard weights, are used in computing each plan. These include:

1. Empty weight of the specific aircraft assigned to the flight.

2. The payload planned for the specific flight.

3. The computed amount of reserve fuel required to qualify the alternate airport designated by the Dispatcher for the specific flight.

4. The amount of holding or detouring fuel, if any, specified by the Dispatcher for the specific flight.

Use of actual weights optimizes this aspect of a flight plan. The amount of fuel required to safely complete each flight is all that is carried.

A route comparison program is used for all long-range flights (longer than 1000 miles). In it the computer analyzes the forecast high-level wind patterns and selects the least-time track.

Altitude and speed (Mach) are optimized in all flight plans, regardless of stage length. In selecting the optimum altitude(s), the program checks all possible flight profiles at all operable flight levels, employing step-climb and step-descent when wind and temperature conditions along the route indicate that an advantage will be gained.

Mach number is optimized after the program compares computed flight time at standard Mach to schedule flight time. Standard Mach is a pre-selected speed that approximates long-range-cruise speed at heavy weights and was formerly used as the basis for a constant-Mach-cruise program. If the computed time is equal to or longer than scheduled time, a standard Mach plan is produced. If the computed time is less than scheduled, the program will recompute at successively lower Mach numbers until scheduled time or long-range-cruise Mach is reached. All flights for which a schedule is not published, specifically charters and ferries, are planned at long-range-cruise Mach to conserve fuel.

In addition to the programs which produce optimum flight plans as described above, several options are available for special cases. These include 5th-pod flight planning for the Boeing 747, planning at a specific altitude and/or Mach, planning at optimum altitude at a specific Mach, blocking altitudes and routes from consideration because of military manuevers or severe weather, etc.

WEATHER INPUT

U. S. Weather Bureau forecast data is received from the National Weather Service twice a day. Each set of data received is essentially a 30 hour forecast from the time the weather observations were taken. The first four hours after the observations are used by the Weather Bureau to analyze the data and prepare the forecasts which then cover the subsequent four, six-hour periods. These data are input into the computer on the basis of the Marsden square grid and at pressure altitudes of 18, 24, 30, 34, and 39 thousand feet.

The flights to which INS equipped aircraft are assigned are designated "Honker" flights. At specified locations on these flights, wind and temperature data is determined from the equipment on board and radioed to the ground. Company meteorologists analyze this data and make appropriate changes to the forecasts stored in the computer weather model. The B-747 fleet (18 airplanes) and the DC-8-62 fleet (9 airplanes) are equipped with INS.

The weather model covers the geographic area of the continental U. S. and the Pacific to Hawaii. The system has the following limitations:

- Data input points are relatively far apart. The dimensions of the Marsden squares about 150 n. miles north-south and 240-260 n. miles east-west. Significant weather variation can occur within the confines of such an area.

- Linear interpolation is used to obtain output between data input points in both the horizontal and vertical planes.

- Weather Bureau input data tolerances are generally $\pm$ 50 knots for wind and $\pm$ 5° for temperature. UAL, through use of company meteorologists and "Honker" flights, attempts to keep data tolerances to $\pm$ 20 knots and $\pm$ 2°.

- Only 27 out of a total of more than 350 aircraft are equipped with INS for use in providing updated weather information. However, these are long range aircraft and do have relatively high utilization.

As Weather Bureau observation data is received, it is used to check UAL modified forecasts for that time period in a program to verify the validity of the forecast. In recent months, on 90 percent of trips for which weather was forecast, the temperature error was within $\pm 4°$; and on 80 percent of the trips, the error was within $\pm 2°$.

PERFORMANCE DATA

Airplane performance data used in pre-flight planning consists of the following:

- Time, fuel, and distance to climb to any altitude as a function of takeoff weight and temperature, including allowances for takeoff and maneuvering. Only a single climb schedule is used. It is predicated on use of an engine thrust rating, i.e., Maximum Climb Thrust, and a constant indicated airspeed to some altitude followed by climb at constant Mach number.

- Maximum initial cruise weights for various altitudes as a function of temperature for the appropriate engine thrust rating. This information is used to determine altitude capability both initially and for step climb considerations.

- Cruise specific range data as a function of weight and altitude at 0.01 Mach intervals over the cruise speed range.

- Time, fuel, and distance to descend from any altitude including a standard allowance for approach and landing. Only a single descent schedule is used and approach allowances are not tailored for specific destinations.

- Holding fuel consumption data which allows planned total fuel load to be adjusted to account for anticipated delays.

These data are processed with curve fitting routines and are stored in the flight planning computer in the form mathematical coefficients.

The initial source of the airplane performance data is the airplane manufacturer. That data is checked on performance guarantee flights, new airplane acceptance flights, and during an initial service period evaluation, and is adjusted as necessary. A small amount of cruise data is recorded on each flight of each airplane in service and a periodic performance audit is conducted on each airplane and each fleet. The results of these audits are used to (1) identify mechanical problems on individual airplanes, i.e., engine deterioration, high drag, faulty airspeed systems, excessive pneumatic bleed air losses, etc., and initiate corrective action, and (2) form the basis for adjustment of the flight planning performance data to reflect that specific fleet of airplanes. Climb and descent data is checked only if flight crew comments indicate it is needed. UAL has the expertise and capability to modify basic airplane data and develop modified flight planning computer input data.

ACCURACY

The accuracy of a flight plan is, of course, dependent on the accuracy of the weather, weight and performance data used, the calculation methods, the assumptions made and the techniques used to actually conduct the flight. Any attempt to assign accuracy values to each of the foregoing variables and combine them to get a final measure would result in a detailed statistical analysis. Instead, weather and performance data accuracy have been touched on in their respective discussions; calculation methods are those generally accepted in the industry and are of known accuracy; assumptions, particularly those related to departure and arrival fuel and time allowances are under continual re-evaluation; and, in general, United's more than 5,000 flight crew members pay close attention to the computer generated flight plans.

The most recent one year period shows that monthly averages of actual fuel used exceeded planned fuel by 50 to 200 pounds per flight. This is based on a system having about 1500 flights per day varying in length from less than 100 to more than 4000 nautical miles in equipment ranging from early generation DC-8's to B-737's to B-747's. It is recognized that average values tend to mask occasional large variations. Under unfavorable conditions such as unanticipated high enroute temperatures or headwinds or adverse ATC descent and approach routing, it is possible to use 5 percent more fuel than planned on a particular flight. However, the high degree of confidence flight crews place in the computer generated flight plans indicate such large variations from plan to be the exception instead of the rule.

ATC INTERFACE

Flight plans for certain specific flight segments do not vary from day to day and, once approved by ATC, are stored with them and considered to be standing flight plans. Most medium to long range flight plans are not "center stored" in this manner but instead are submitted before each trip. ATC is cooperative in assigning the altitudes and routes as produced by the flight planning computer. In the event they are not able to accommodate the flight as requested, they generally offer a choice of (1) an alternate altitude, (2), an alternate route, or (3) a departure delay which would allow the requested area to clear.

ATC plans to implement Fuel Advisory Departure procedures at Chicago's O'Hare airport. These procedures will be activated whenever conditions in the O'Hare area are expected to cause enroute delays (holding) for flights arriving from various selected locations. Flights scheduled to depart from these locations to O'Hare will be given the choice of departing on time and holding enroute or holding on the ground at the originating location. If the ground delay is chosen, ATC will establish an Expected Departure Clearance Time that will include a delay equal to the expected enroute delay. The flight could also be exposed to an enroute delay of up to one hour.

IN-FLIGHT PLANNING

ON BOARD COMPUTATIONAL CAPABILITY

The present day capability to do on board computations is quite limited with no general purpose automatic data processing computers installed on any airplane in the fleet.

In-flight, performance related, computations are done with the time honored "Jepps" type hand held computer. The ground based flight planning computer is also used in a "flight-following" role whereby periodic mandatory radio position reports from airplanes in flight are fed into the computer which updates its file on the flight and projects the time at which the airplane should reach its next reporting point.

There are various highly specialized computers on board for other purposes, the output of which might be used and modified to solve performance problems. These include autopilot computers, central air data computers, inertial navigation systems, and autothrottle computers. Not all airplanes in the fleet are equipped with all of the foregoing.

AREA NAV CAPABILITY

The present area navigation capability on United's fleet consists of one test installation. A cooperative evaluation program with the equipment manufacturer is underway to aid in refinement of the hardware and to provide United operational experience with area navigation.

WEATHER INPUT

Weather information in the terminal areas for both departure and approach is obtained by the flight crew from ATIS (Automatic Terminal Information System).

In flight, updated weather information is not automatically provided to airplanes in flight. The flight crew, at their option, may monitor radio frequencies of aircraft preceding them on the route they intend to fly in hopes of obtaining pertinent reports, or, they may request updated weather information. This information would come from the same sources as does the flight planning weather data; specifically, it would include updated National Weather Service forecasts modified by company meteorologists based on reports from flights in the area of interest.

PERFORMANCE DATA

The airplane performance data available to the crew in flight is contained in the company flight manual. Some of the performance data in the flight manual serves as direct input data for the automatic flight planning program and considerable effort is expended to maintain compatibility between these two sources of information.

The flight manual contains a Flight Planning Table which provides time and fuel requirements as a function of trip length and altitude for a specified speed schedule. The table includes wind and weight adjustments. It is used primarily to verify the computer generated flight plan for any given trip, although, it may also be used manually to develop a flight plan. Maximum initial cruise weight data is provided for various altitudes as a function of temperature for the appropriate engine thrust rating. This information is used to determine altitude capability both initially and for step climb considerations. Cruise control data consists of thrust setting required to maintain the desired Mach number as a function of altitude and weight, and the expected resulting specific range under those conditions. These data are provided at 0.01 Mach intervals over the cruise speed range, at long-range-cruise speed, and in some cases, at selected constant indicated airspeeds. Minimum drag speeds and holding configuration fuel flow data is supplied. Initial buffet speeds, stall speeds, and maximum operating speeds data provide guidance in planning. In addition to the flight manual data, the computer generated flight plan for the trip has summary flight plans for several altitudes other than the one finally selected for the trip.

Various other operators throughout the country and the world utilize supplemental data. These items are mentioned here because, even though United does not use them, they are definitely within the state of the art and their usage is a matter of operating policy, automation, and route requirements. The items in mind are optimum altitude charts, wind-altitude trade charts, how-goes-it charts, climb speed adjustments for wind, temperature, and weight variations, and step climb guidance.

AMBIENT ATMOSPHERIC CONDITIONS

The current UAL procedures to minimize fuel consumption with regard to ambient atmospheric conditions consist entirely of adverse condition avoidance. In general, if actual performance is matching or better than that expected from the computer generated flight plan and ride quality is adequate, no particular attempt is made to find more favorable atmospheric conditions.

Adverse winds, temperatures, and weather conditions are avoided by altitude changes and diversions from intended route with no formal procedure set forth, but relying on the good judgement of the flight crews to consider least fuel expenditure, safety, and service to the customer.

Flight crews do have the prerogative to deviate from planned altitude, speed, and routing to take advantage of favorable atmospheric conditions.

ATC INTERFACE

Air traffic control cooperates in granting requests for changes in altitude and routing when, after a flight is enroute, it becomes apparent that the change will save fuel.

Jet powered air transports are most efficient at high altitudes and the most efficient way to fly an airplane in cruise is to allow the altitude to increase as the airplane weight reduces with fuel usage. This concept is called "climb-cruise" and is not allowed within the air traffic control system because of the difficult traffic separation problem it presents. Instead, the airplane is flown at a constant altitude until the weight has decreased enough so that the airplane can ascend several thousand feet in a single "step climb," thereby attempting to approximate the efficient cruise climb profile. Generally, for purposes of traffic separation, these step climbs were in increments of 4000 feet. However, in recent months, ATC has been willing to grant 2000 feet step climbs on request if conditions permit; this allows a closer approximation to the cruise climb profile. Experience with ATC has been that requests for clearance to step climb are granted as a matter of course and without delay.

Routing and altitude changes may also be desirable if unplanned, adverse wind or weather conditions are encountered.

Air Traffic Control centers are quickly becoming aware of the desirability of maintaining a high altitude cruise condition for as long as possible before beginning the descent to the arrival terminal area. ATC is allowing pilots to descend at their own discretion to a much greater extent than in the past.

The arrival in a terminal area and subsequent approach to landing presents unique ATC problems and is the least efficient portion of the flight. The requirement is to bring numerous aircraft, arriving from different directions at different altitudes, into a line for landing on a single, or a very limited number of runways by constantly controlling the speed, altitude, and position of each aircraft. Many times this results in holding delays or circuitous routing at low altitudes where fuel consumption is high. Much has been done to increase ATC personnel staffing levels and qualifications, and with wider implementation of the semi-automatic ATC system now in development, it is anticipated that marked progress will be seen in this area.

AUTOPILOT AND FLIGHT DIRECTOR MODES

It is standard practice to use autopilot and flight director modes of operation on all but the briefest trip segments. This practice is generally acknowledged to consume less fuel than would manual control, but recent quantitative data on fuel conservation via automatic rather than manual flight is lacking. The autopilot is used in climb and cruise phases of flight while the flight director is used on approach. No specific new or different uses of autopilot or flight director modes have been adopted as a result of recent fuel conservation emphasis.

Present autothrottle systems are designed for use primarily in the terminal area and approach regime as a result of the demands on the pilot's time and attention during landing in very low visibility conditions. The DC-10 Autothrottle/Speed Command systems can be, and is, used for automatic speed control during climb and cruise. Although the system response characteristics could be improved, such speed control systems offer good fuel saving potential by reducing power and, consequently, fuel flow as the airplane gets lighter.

ATC IMPACT ON FUEL CONSERVATION EFFORTS

The Air Traffic Control system plays a major role in an air carrier's overall fuel conservation efforts. Studies can be made and operating policy and procedures can be changed, but if the results of these actions do not fit into the existing ATC system, or if the ATC system is not flexible enough to accept them, the effort produces nothing.

ATC has been cooperative in accommodating requests for slower climb speeds, reduced cruise speeds, higher, more efficient cruise altitudes, altitude changes in flight, and delayed descents.

There are, however, several areas under study by ATC which present problems not yet solved. United's only long overwater segment is from the West Coast to Hawaii. Radar coverage is available only from the ground stations at each end of the flight. Without positive position information enroute, ATC will not allow altitude changes, i.e., step climbs, thereby requiring a flight to maintain its initial altitude over the whole segment. This, of course, is not efficient from a fuel standpoint. An extension of this problem is that alternate (and longer) routing is required as the traffic density increases; again, as the result of lack of positive position information.

Terminal area arrivals and departures are conducted in accordance with standard predetermined routing and procedures modified as necessary by the demands of traffic. These are known as Standard Terminal Arrival Route (STAR) and Standard Instrument Departure (SID). Many of these standard procedures involve circuitous routing which must be done at low altitude and therefore is inefficient. When these procedures must be modified to meet the demands of traffic, invariably, airplanes are asked to slow down to allow other aircraft to complete their maneuvers. Many times this slowing requires the use of high lift devices which increases the drag and, consequently, the fuel flow.

The fuel conservation efforts made by United to date have been predicated within the existing ATC framework and, therefore, have been generally acceptable to the ATC system. Adverse impact on these efforts has lessened as ATC personnel became aware of the fuel situation and the effects of their actions on fuel consumption. One of the most potentially productive areas for fuel conservation is in direct routing of aircraft within a system flexible enough to accommodate optimum climb and cruise speeds.

RESEARCH AND DEVELOPMENT

Research and development efforts in the air transportation industry vary with the field of research. Basic research is usually done by research institutions; equipment manufacturers do applications research and development work as required to produce a safe, marketable product. Air carriers occasionally engage in research and development activity where safety is at stake or where definite economic gains are clearly to be had. Much of the technology of fuel conservation has evolved over a long period of time with no integrated research effort. In recent years, the airframe manufacturers have become a collection point for fuel saving ideas which have been developed both by themselves and by the air carriers.

Air carriers generally are not in a position, either from a staffing or an economic standpoint, to undertake detailed research projects. They will, of course, develop techniques and adopt whatever procedures they reasonably can to enhance fuel conservation. However, for guidance, they will tend to look to the airframe and equipment manufacturers who will naturally consider fuel conservation in developing new products and to research institutions who have traditionally investigated areas of general basic interest. Also, air carriers in general and United in particular, are amenable to contract research of this type when the equipment involved is acceptable on passenger carrying aircraft without extensive certification effort. Research in the following areas could prove beneficial in reducing fuel consumption. It should be noted that implementation of procedures or equipment in one area of concern may adversely impact other areas of the overall operation; future research efforts should be conducted with this in mind.

CURRENT ON-BOARD AVIONICS

The design concepts of avionics systems aboard airplanes presently being flown by major air carriers range from that of the 15 year old early DC-8 and B-707 aircraft to the sophistication of the DC-10 and L1011. One area that all these aircraft and avionics systems have in common is the ATC environment in which they operate. Earlier comments about the ATC impact on fuel conservation efforts noted that present efforts were within the framework of the existing ATC system. If ATC were able to allow direct climbs and descents without substantial routing, holding at intermediate altitudes, and detailed speed control, significant fuel saving could be achieved without change to the on-board avionics. Although attention is being focused on ATC, it should be stressed that implementation of the results of research in many areas will be dependent on the capability of the ATC system to make proper use of the implemented systems.

Optimum climb and descent profiles are not commonly known or flown. Determination of these profiles could be followed by an investigation of the ability of present day autopilots to be used to fly these profiles. Some optimization of selected autopilot modes might result from these investigations, adding further benefits.

Present day autothrottle systems have been designed for use primarily in the terminal area and approach regime. During the enroute pate of a flight, i.e., cruise and the higher altitudes portions of climb and descent, use of the autothrottle is either prohibited or system response is less than satisfactory. Further development of autothrottles for enroute usage should be investigated.

FUTURE ON-BOARD AVIONICS

The direction of development of future on-board avionics will, of course, be dependent on the ATC environment in which it will operate. This environment is evolving along lines recommended by the DOT Air Traffic Control Advisory Committee and should accommodate future on-board avionics discussed here, although, the avionics and ATC systems may not always be compatible during introductory periods. Evidence of such incompatibility may be had in looking at the introduction of Inertial Navigation System (INS) equipment; ATC initially could not accommodate the great circle routes generated by this equipment.

The previous discussion of present on-board avionics addressed VOR navigation which requires flying from one VOR station to the next point-to-point, in some round-about or zig-zag fashion to get from origin to destination depending on the locations of the intermediate VOR stations. The most discussed advantage of area navigation system (RNAV) is the ability to use the intermediate VOR stations for position information while flying a direct route from origin to destination. Undoubtedly, significant fuel saving can be realized from this method of operation. However, within the framework of the present ATC system, such routing cannot always be accommodated. Hence, the economic justification for installation of RNAV may be found in management of aircraft in climb and descent, the so-called vertical guidance function of VNAV. Implementation of vertical guidance does not depend on the existance of an RNAV oriented ATC system and could be accomplished within the present VOR system. Recent industry emphasis has been to use VNAV to generate straight line ascent and descent paths as an aid to air traffic control. However, these straight line paths are not economical and further efforts are required to assess both the traffic control and the fuel conservation potential of VNAV.

Electronic flight instruments/displays are being developed within the industry today which are likely to be used as primary flight instruments, serving as the major display interface between the navigation system and the pilot. The air transport industry has traditionally attempted to set standards for navigation and display equipment. Since the nature of the new devices allows a wide variety of display possibilities, it should be stressed that the results of human factors research regarding display effectiveness and display compatibility with airplane performance and ATC environment all be in hand before display standards are set for this equipment.

The availability of navigation systems which provide automatic, precise position information and the ability to fly virtually any desired flight profile has brought forth the idea of a Flight Management System. This system would be based on the above mentioned navigation system, an airborne bulk data storage device and an airborne high speed computer. Stored data would include an airline's entire route structure including SID, STAR, enroute facilities/waypoints, and airport landing and takeoff data. Coupled with an electronic flight display and, possibly, the aircraft autopilot and autothrottle systems, such a system could provide automatic flight plan execution including terminal area operation. Every bit as important as automatic flight plan execution would be the ability to calculate on board, based on current ambient and flight conditions the optimum profile and speed, and vary from the pre-determined flight plan to achieve the optimum flight condition. Such a system is complex, but certainly within the realm of today's technology. Research will be required to determine (1) the extent to which automatic flight plan execution is feasible, (2) the method in which profiles and speeds are optimized, and (3) the magnitude of the gains obtainable by optimizing profile and speed rather than flying the flight plan.

ESTIMATES OF FUEL SAVING

PRE-FLIGHT PLANNING

The section on pre-flight planning discussed many activities which contribute to a fuel efficient operation. In some cases, such as accurate weather forecasting, it is not possible to quantify the fuel saving resulting from this activity.

The policy decision to reduce cruising speeds did produce an overall definite, measurable fuel saving of 2 to 4 percent, or on the order of 55 million gallons of fuel annually. Savings of this magnitude are projected by the airframe manufacturers as well.

The greatest hinderance in attempting to quantify fuel saving is lack of an adequate baseline. For example, computer optimization of flight plans has evolved over the years and is presently a way of life; on the other hand, there is no applicable experience of manual flight planning for a large fleet which can be used as a comparison with current practice.

IN-FLIGHT PLANNING

Flight crews are encouraged to use their judgement and the means at their disposal to save fuel where practical. Since such activity is usually in response to encountering unplanned operational conditions, it is not possible to establish generalizations about the amount of fuel saved. Any operational condition which would lend itself to generalization is considered and included in the pre-flight planning for subsequent operations.

IMPACT OF AVIONICS

United Air Lines has not done detailed analysis of the potential benefits in terms of fuel saving to be derived from application of advanced avionics. The area navigation evaluation program now in progress has as one of its goals an economic evaluation of the system. It is anticipated that some small fuel saving might be realized from the direct routing lateral guidance feature of area navigation.

The potential for saving fuel through use of avionics appears to be greatest in the area of vertical guidance in all phases of flight.

1. Optimization of climb speed schedules for existing conditions could reduce climb fuel consumption by more than one percent.

2. Use of cruise-climb technique enroute to fly at the optimum altitude could reduce cruise fuel consumption by one-half to two percent.

   Automatic flight plan execution to maintain planned cruise speed possibly through use of autothrottles, could save additional fuel. Excess cruise speed of .01 Mach number increases fuel consumption by one to two percent.

3. Direct descent routing at idle thrust, without excessive maneuver time at low altitude could cut descent fuel by as much as one-third. The descent and approach in the present operating environment varies with operational factors so the quoted saving could not be realized in all cases. However, vertical guidance in descent appears to offer the potential for significant fuel savings.

CONCLUSIONS

A summation of the pertinent points revealed by this study follow.

- Preflight planning as it now stands is adequate with the exception that more accurate and up-to-date weather information would be desirable.

- In-flight alteration of flight plans are subject to a wide variety of operational conditions, but better information about the existing conditions, i.e., wind shears, best step climb points, etc., could result in better decisions by the flight crews.

- The Air Traffic Control system is developing in accordance with a master plan which holds promise. The importance of ATC in saving fuel cannot be overstressed.

- Current on-board avionics are presently being used near their full potential with regard to saving fuel.

- Vertical guidance in all phases of flight holds the greatest promise for fuel saving if the ATC system can accept direct climb and descent routing and enroute altitude variation such as cruise climb or reduced altitude separation. Much of this vertical guidance could be afforded by an on-board system such as area navigation. Research will be required to determine the optimum use of the equipment and the magnitude of the potential fuel saving.